Petrology and origin of beach sand along the Rottnest Shelf coast, Southwestern Australia

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Abstract

A petrological study of beach sands along the Rottnest Shelf coast of southwestern Australia shows that there is wide variety of grain types derived from a range of sources. The main grain types are quartz, lithoclasts, molluscs, calcareous algae, foraminifera, echinoids, felspar and heavy minerals. To illustrate regional variability in beach sand composition four main grain categories were used: quartz, felspar, lithoclasts and skeletons. The distribution of these grain types along beaches shows distinct regional patterns within each of the five sectors between Geographe Bay and Dongara, reflecting variation in source type, biotic assemblages and coastal processes. The Geographe Bay, Leschenault-Preston and Wedge I-Dongara sectors exhibit relatively uniform compositional trends. The remaining sectors exhibit marked compositional variation related to their rocky shores, pocket beaches, cusps and accretionary sediment cells.

Quartz dominates the Geographe Bay and Leschenault-Preston sectors, but overall there is a decline in quartz to the north. Skeletons dominate the Wedge I-Dongara Sector, but may be locally abundant in the other sectors where there are nearby seagrass meadows or rocky shores. Lithoclasts are abundant near sites of eroding coastal limestone. As a consequence, such as in the Cape Bouvard-Trigg I and Whitfords-Lancelin sectors, the distribution of skeletons and lithoclasts may be markedly restricted geographically. Regionally, there also is a decline in abundance of felspar and heavy minerals to the north. The results highlight several trends in beach sand composition that are useful in understanding littoral transport, coastal processes and coastal management.

Introduction

The study of sediment provenance is the investigation of composition, texture and distribution of grains within sediment bodies with a view to determining their source or origin. Such data can indicate the relative importance and relationships between potential sediment sources and suites, and can provide insight into whether sediments are relict, or actively transported from distant sources, or thoroughly mixed, *etc*. Sediment provenance is a well established technique to derive such answers (Earley & Goodell 1968, Carver 1971, Windom *et al* 1971, Scheidegger & Phipps 1976, Browne *et al* 1980).

The essence of specifically applying a petrologic approach in provenance studies, rather than a textural one, is that by use of compositionally diagnostic sand grains (particularly if their origin or source is discrete) it is possible to map the final distribution of grain types to indicate one or more processes. The occurrence, absence, or abundance of specific grain types may be due to: 1 transport into the site; 2 generation at the site; and 3 dilution at the site by other incoming grain types.

The widespread nature or otherwise of particular grains therefore can indicate the amount (or lack) of dispersion along a given transport pathway. Conversely, the occurrence of discrete pockets of sediment with specific grain types could signal no transport to and from the study site, or for skeletal grains, generation within the site and no transport from it. Petrologic/provenance studies thus provide information on the degree of dispersion/transport in the natural system by utilizing diagnostic grains of known source. The advantage of such studies over those that utilize artificially stained sand is that natural grains reflect patterns of transport and dispersion that have occurred over a long term.

A petrological/provenance study can be successfully applied to beach sands of southwestern Australia for a number of reasons. Firstly, there are many distinct grain types with variable sources and variable age. Secondly, the beach is the zone of maximum sediment transport, and hence dispersion pathways, or lack of them, can be highlighted by use of provenance studies. Thirdly, nearshore/inshore coastal processes result in sediment being transported onshore and thus the beach zone can reflect input from nearshore/inshore sources as well as those alongshore. Finally, because beach environments tend to produce sediments of limited textural variation, textural attributes (such as grain size, shape, and sorting) alone cannot resolve provenance patterns.

This paper describes the principles, methods and results of a sediment petrology study of beaches of the Rottnest Shelf coast of southwestern Australia. The relevance of these results to local coastal processes of transport also is discussed. The principles and methodology of provenance analysis presented are applicable to other coasts with similar compositional diversity of sediment sources, and can provide information useful for determinimg sediment budgets and coastal dynamics at various scales of reference.

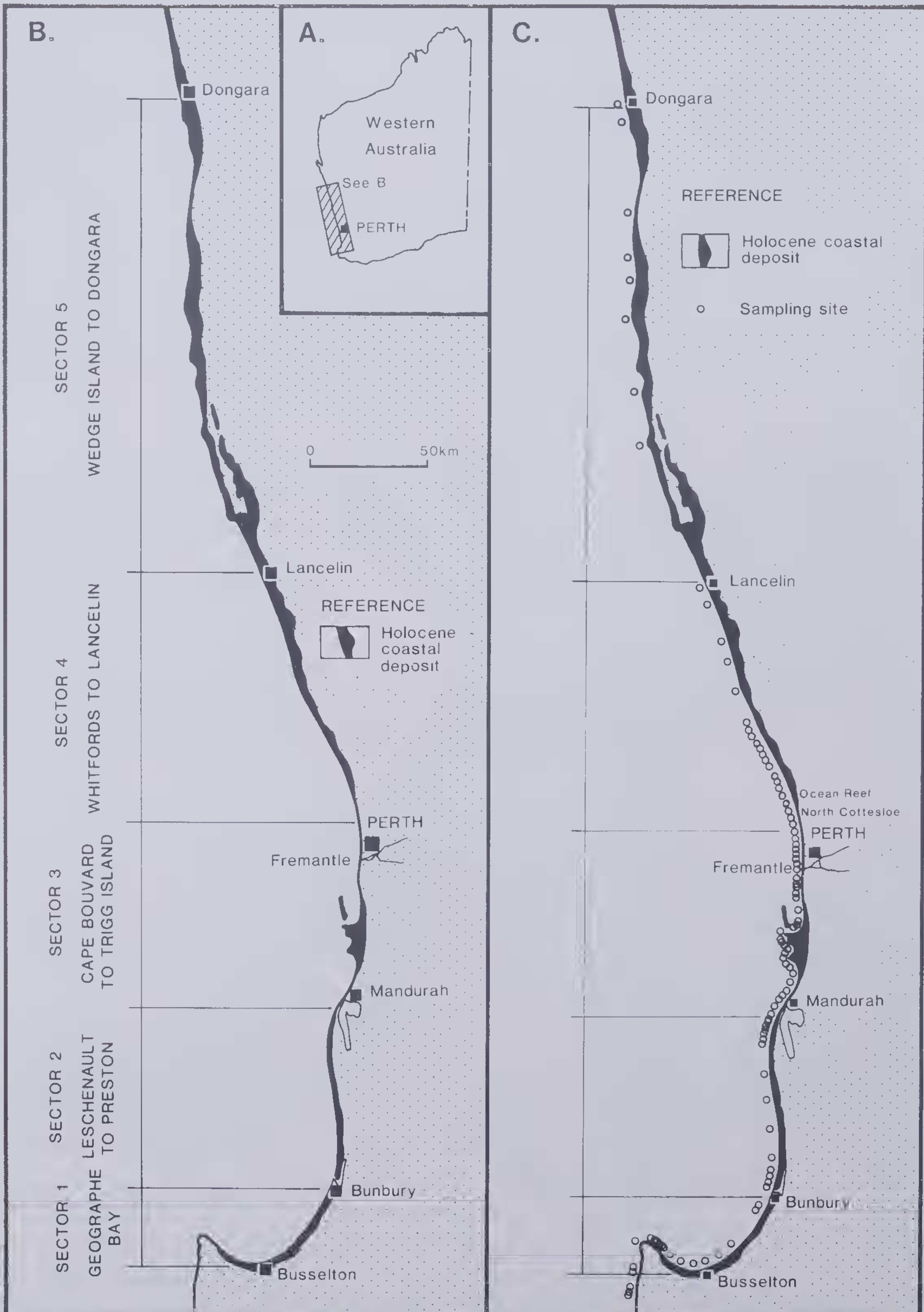

Figure 1 A & B Locality diagram showing coastal sectors of southwestern Australia (after Searle & Semeniuk 1985). C Location of sampling sites within each sector.

Methods

The sands of long uninterrupted beaches as well as the discrete pocket beaches of scalloped limestone rocky shores were sampled in this study (Fig. 1).

Three scales of sampling strategy were adopted. At the larger scale sampling was designed to encompass sediment compositional trends that distinguish the various coastal sectors of Searle & Semeniuk (1985). Sampling at this larger scale was carried out along the shore on a >10km spacing. All sectors were sampled in this manner. At the medium scale, in selected areas within each sector, such as the coast between Quinns Beach and Whitfords Beach, or between South Fremantle and Madora Bay, sampling of beach sands was carried out at a regular 0.5-1km spacing. At the smaller scale, in some selected areas of detailed study such as pocket beach systems along scalloped limestone rocky shores (Semeniuk & Johnson 1985), sampling was at intervals of 100-200m. At each sampling locality triplicate samples of surface sediment were collected in the swash zone within an area of 50m of beach shore length. Each sample was 100-200g in quantity and composed mainly of medium and coarse beach sand.

In the laboratory the replicate samples were dried in preparation for petrographic analysis. Because this investigation was a petrological study, the samples were not sieved so that the sediment composition across the full range of grain sizes could be determined in thin section. Each replicate sample was sub-sampled to yield *c* 2 cm^3 and impregnated with blue-dyed resin which accentuates the intergranular spaces and intragranular porosity under the microscope. Each of the impregnated blocks was cut into a standard thin section and stained for felspar. The thin-sections were petrographically analysed using a binocular polarizing microscope with an attached automatic point counter. For each slide between 300 and 500 points were counted (Galehouse 1971). Eight categories of grain were counted: quartz, felspar, carbonate lithoclast, mollusc, calcareous algae, foraminifera, echinoderm, and the heavy mineral suite. These were subsequently aggregated into five categories by amalgamating all the skeletal grains, as some skeletons were not found to be present in sufficient numbers. Each of the triplicate samples was analysed separately and a mean abundance (± SD) of grain types calculated for each sample site. The standard deviation was almost always less than 10% of the mean, indicating good reproducibility of sampling techniques and petrographic analysis, and relative homogeneity of sampling sites (Fig. 2).

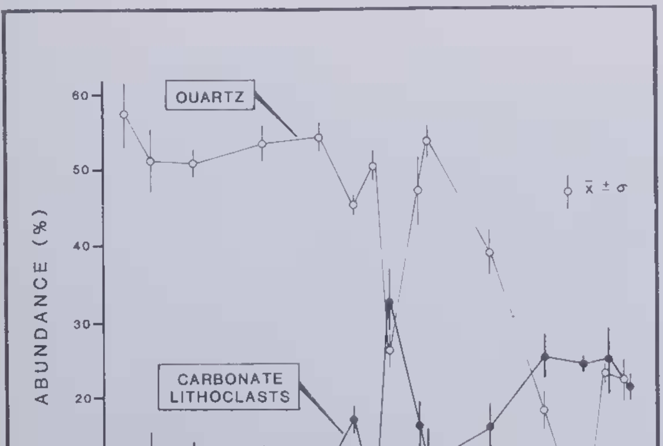

Figure 2 Detail of section of coast between Cottesloe and Ocean Reef showing quartz and lithoclast content of beach sands. Note the small standard deviation with respect to the mean abundance for these samples.

The identification of skeletal fragments in thin section is based on sections made from known standards. The standards provided definitive information on crystal size, crystal orientation, foliation, *etc* for each phylogenetic group as well as for distinct species. These standard thin sections supplemented information on identification of skeletal remains in thin section published by Bathurst (1975), Majewski (1969), Scholle (1978) and Flugel (1982).

Regional setting

The coastal zone of southwestern Australia is the seaward portion of the Swan Coastal Plain (McArthur & Bettenay 1960), and is composed of Holocene sediments and/or Pleistocene materials, which are part of the Phanerozoic Perth Basin (Playford *et al* 1976). The coastal environment of SW Australia encompassing the inner Rottnest Shelf that adjoins the Swan Coastal Plain has been subdivided into five sectors by Searle & Semeniuk (1985). Each sector has its own ancestral geomorphology, processes of sedimentation-erosion-transport, stratigraphic evolution, modern coastal geomorphology, and its own suite or pattern of distribution of sand grain types.

The coastal sectors are (Fig.2): **1** Geographe Bay Sector, a broad, open, north-facing embayment characterized by a low hinterland and simple submarine bathymetry; **2** the Leschenault-Preston Sector, characterized by a system of barrier dunes and lagoons, and a simple submarine bathymetry; **3** the Cape Bouvard-Trigg Island Sector, characterized by a complex bathymetry of marine ridge-and-depression morphology founded on Pleistocene limestone, and distinct Holocene sediment accumulations forming beachridge plains; **4** the Whitfords-Lancelin Sector, characterized by marine ridge- and-depression morphology, limestone rocky shores and isolated accretionary cusps of Holocene sediment; and **5** the Wedge Island-Dongara Sector characterized by a complex nearshore bathymetry of ridges-and-depressions, limestone rocky shores erosionally scalloped at a large scale, extensive shoreward migrating dune fields and asymmetric accretionary cuspate forelands of Holocene sediment.

Regardless of the variability of the geomorphology of the various sectors, the occurrence of a littoral zone, along which sand is transported, provides a common thread to the entire Rottnest Shelf Coast System (Searle & Semeniuk 1985). The shorelines are of 3 types: **1** sandy beaches, **2** limestone rocky shores alternating with sandy pocket beaches, and **3** limestone rocky shores. The extent and/or abundance of these shore types varies according to location: sandy shores are more common south of Perth; rocky shores are more common north of Perth. Beaches in this region have been subdivided on normal global criteria into shoreface, foreshore, backshore and beachridge/dune environments (Semeniuk & Johnson 1982). Rocky shore environments are complex, with cliffs, breccia wedges, shore platforms and breccia pavements (Fairbridge 1950, Semeniuk & Johnson 1985), but also have local sand accumulations in pocket beaches and sheets.

Grain types of the beach sands

Beach sands of the Rottnest Shelf coast contain the following main categories of grain types, many of which are fragments of siliceous crystals or marine skeletons: quartz; lithoclasts; molluscs; calcareous algae; foraminifers; echinoids; felspar; and heavy mineral suite. In addition, locally, there are fragments of barnacle, sponges, bryozoans and crustacea. A description of the main grain types and their potential source is presented below.

Quartz. Quartz grains occur in beach sands as medium to very coarse sand, well to very well rounded, commonly colourless but some are yellow because of iron compounds in microscopic cracks and pits on the grain surface. There are several potential sources of quartz sand on this coast. Yellow to brown quartzose sand occurs as sheets on parts of the inner Rottnest Shelf (Collins 1983, Searle 1984). These sheets were formed by the reworking of surficial subaerial sand deposits by the rising post-glacial seas. Unconsolidated Pleistocene sand dunes overlying the limestones along the coast are composed predominantly of quartz. The Holocene dunes of the modern coast also may contain up to 90% quartz (Semeniuk & Meagher 1981). Other lesser sources of quartz sand are the Pleistocene limestones; although variable, the quartz content of these limestones is commonly *10-20%.*

Lithoclasts. Carbonate lithoclasts are present as well-rounded, fine to very coarse sand-sized grains, and locally as gravel and cobbles. The lithoclasts typically contain sand-sized skeletal grains, pre-existing carbonate lithoclasts, minor quartz, and traces of heavy minerals. The lithoclasts are commonly cemented by a complex spectrum of microcrystalline, acicular and sparry carbonate cements. The ultimate sources of lithoclasts are the eroding rocky shores and islands of the coast. However, the unconsolidated Pleistocene and Holocene dunes in the region also contain variable quantities of lithoclast material (up to 50%). Although lithoclasts are originally derived from limestones, unconsolidated dunes are probably the most profuse source in the contemporary system.

Molluscs. Mollusc skeletons are present as sand and gravel fragments, and as whole skeletons, and vary in condition from pristine unbroken forms to well-rounded fragments. Mollusc material was identified mainly to class level. Some material was identified to generic and specific level for organisms that indicate specific environments; these skeletons include *Donax, Glycymeris, Brachidontes, Ninella, Marmostoma* and *Thalotia*, because they can reflect derivation from beach, rocky shore and seagrass meadow environments. For purposes of this paper discrimination of molluscs to generic or specific level is not provided, but such detail would be useful in studies located on small scale to medium scale sites.

The sources for mollusc grains are the benthic assemblages in the region. Seagrass meadow assemblages provide *Thalotia* and a host of other gastropod and bivalve species (Semeniuk & Searle 1985). Molluscs of the beach and inshore sand zone are mainly *Donax* and *Glycymeris*. Molluscs of the rocky shore include *Brachidontes, Ninella, Marmostoma, Dicathais* and *Haliotis.*

Calcareous algae. These skeletons occur as well rounded sand-sized fragments, or sand-sized disaggregated stem/leaf segments. The common calcareous algae are derived from seagrass meadows and algae-turf covered rocky shores. In this study, discrimination below the family level, even for those calcareous algae that are environment specific, was not attempted.

Foraminifera. Whole tests of foraminifera occur as sand sized components and are readily identifiable to generic and specific level. However, only *Marginopora* tests and fragments are common enough to be included in the study. The *Marginopora* are derived from seagrass meadow environments.

Echinoids. Spine and plate fragments of regular echinoids occur as sand-sized components, but are not common. They indicate derivation from a rocky shore or rocky pavement environment.

Felspar. Felspar grains occur as medium to very coarse sand. Most of the felspar occurs where rivers draining the granitic uplands have discharged sand onto the shelf during the Quaternary. Elsewhere felspar occurs in discrete patches of sand related to a relic offshore source. Felspar is also reworked from yellow dune sands overlying the coastal limestone.

Heavy mineral suite. The suite of grains termed heavy minerals includes rutile, ilmenite, tourmaline, garnet, leucoxene, monazite, magnetite, hornblende, augite and others (Baxter 1977). These minerals typically are fine sand- to very fine sand-sized. Their occurrence is widespread but they tend to occur most abundantly in Sector 1. In this study because of their overall low abundance when viewed regionally, differentation beyond "heavy mineral suite" was not warranted.

Other miscellaneous grains. Other grains, mainly skeletal, are described here only for completeness. These grains may be readily distinguishable in thin section and frequently are diagnostic of specific sources. The grains include barnacles, sponges, bryozoa, brachiopods, crustacea, vertebrate ossicles, intraclasts derived from beach rock, rock clasts eroded from basalt headlands (*eg* at Bunbury), and granite/ gneiss clasts and mica eroded from granitoid rock coasts of the Leeuwin Block. However, because of their low general abundance these grains were not used in this study.

Sources of the grain types for sediments in the region

There are numerous sources for the various grain types of the Rottnest Shelf coastal beaches. Some of these sources are currently manufacturing raw material; some are relict and slowly contributing specific grains; and some are eroding terrains yielding, again, a mixture of specific grain types. The main sources of the grains of the coastal beaches are: seagrass meadows; rocky shores; sandy beach and inshore zone; eroding yellow sand dunes; eroding estuarine deposits; eroding Holocene sand deposits; relict shelf sediment; eroding beach rock; and fluvial environments.

Seagrass meadows. Seagrass meadow environments, comprised of seagrasses, their epibionts and benthic fauna, are a major site of carbonate grain productivity in this region and thus a major source of skeletal grains. Seagrass meadow environments can produce some 2.2kg/m^2 of carbonate annually (Searle 1984) and much of this material accumulates *in situ*, contributing to an evolving seagrass lithofacies. However, as the banks prograde, shoal and lose their seagrass cover the sediment material becomes available for transport into the littoral zone. The carbonate grains generated include whole tests of foraminifera, bivalves and gastropods, and disaggregated or fragmented tests and skeletons of calcareous algae, bivalves, gastropods, bryozoans, sponges and crustaceans. The main skeletal fragments derived from seagrass meadows that are found in beach sediment are listed in Table 1.

Table 1

Relationship of grain types to the variable sources

	DERIVED GRAIN TYPES	
	sand	gravel
seagrass meadow	molluscs calcareous algae foraminifera	molluscs
rocky shore fauna	molluscs calcareous algae echinoids	molluscs echinoids
sand beaches and inshore zone	molluscs	molluscs
eroding limestone shores	lithoclasts lithoskels	lithoclasts lithoskels
eroding yellow sand dunes	quartz	
eroding Holocene sand deposits	molluscs calcareous algae foraminifera echinoids lithoclasts lithoskels quartz	molluscs lithoclasts lithoskels
relict shelf sediment	quartz lithoclasts	
fluvial environments	quartz felspar	
eroding estuarine deposits	quartz molluscs	molluscs
eroding beach rock	intraclasts	intraclasts

Rocky shores. The rocky shore environment yields 3 broad suites of grain types: whole skeletons and fragments of the resident biota; material from the eroding limestone; and quartz sand (Semeniuk & Johnson 1985). The biota inhabiting rocky shores is varied and includes calcareous algae, bivalves, robust gastropods, sponges and crustacea. The material eroded from the limestone shores are gravel and sand-sized lithoclasts and lithoskels; they include platey, rod-like, irregular and equant gravel-sized lithoclasts (Semeniuk & Johnson 1985), generally equant medium and coarse sand-sized lithoclasts, and whole to fragmented lithoskels (Read 1974). Some of this material is transported shore-wards or alongshore to accumulate in pocket beaches, but some also is transported to any adjoining long stretch of sandy beach in the region. Rocky shores also release quartz sand from the eroding limestone, from exhumed yellow sand-filled solution pipes, and from the quartz sand that blankets the coastal limestone.

Sandy beach and inshore zone. This environment of sand substrates supports benthic fauna of *Donax*, *Paphies* and *Glycymeris*, all of which contribute gravel-sized unfragmented shell and fragmented sand-sized particles.

Yellow sand dunes. Coastal erosion of the Spearwood Dunes invariably reworks the yellow quartz sand sheet that mantles the terrain. As a result quartz sand is dispersed into the shore environment.

Estuarine deposits. Coastal retreat may expose buried former estuarine deposits (*cf* Semeniuk 1985). These deposits are composed of inter-layered mud, shelly mud, shelly quartz sand and quartz sand. Grains derived from these deposits include estuarine shells and fragments, mud clasts and quartz sand, which are transported shoreward into the beach zone.

Holocene sand deposits. Erosion of earlier Holocene sand deposits (*eg* southern Becher Point, or Leschenault Peninsula) provides a wide range of grain types. The entire range of available grain types in the region may have been incorporated into a Holocene sediment sink, and later erosion will re-distribute these same grain types. The most common grains are quartz, skeletons and lithoclasts.

Relict shelf sediment. Sediment in the offshore/nearshore marine environment frequently is relict and is comprised of quartz sand or coarse skeletal sand and gravel. In most instances the relict sediment bodies are preserved because they are largely isolated from contemporary sediment sources. However, slow leakages of relict grains may be supplied to the shoreline by onshore transport.

Beach rock. Indurated beach sand referable to beach rock once formed in the shore zone can undergo erosion and degradation (Semeniuk & Searle 1987) to form boulder-, gravel-, and sand-sized intraclasts. These grain types, however, are not abundant.

Fluvial environment. Direct discharge of sediment from fluvial sources at numerous localities (*eg* Geographe Bay, Collie River, mouth of Swan River, mouth of Moore River) usually is limited by the occurrence of estuaries impounded behind coastal ridges or semi-permanent mouth bars. Entrained riverine sediment thus is retained in the quiescent estuarine environments forming deltas and bar complexes. However, some fluvial sediment consisting primarily of quartz and felspar is still discharged into the marine environment from the rivers of the smaller estuaries during periods of abnormally high flow. Fluvial sediment may also be incorporated into the shore environment where large scale coastal erosion has incised into pre-existing fluvial-estuarine deposits.

Discussion. It is apparent that a variety of grain types may be supplied from individual sources. This may lead to some confusion as to the source for a concentration pattern of a particular grain type. Conversely, some grain types originate from several sources. For instance, quartz is reworked and transported from rocky shores, yellow sand dunes, estuarine deposits, Holocene sand deposits, relict shelf sources, and fluvial environments. Thus the occurrence of local, high- concentration patches of quartz along a beach must be studied in context, by tracing the grains to the source by more general provenance mapping. Some grains are more specific as to source, for example lithoclasts, which ultimately indicate eroding limestones. Also in this regard, environment- specific shells can also be related directly to source (*eg* some species of *Thalotia* derived from seagrass meadow environments, *Ninella* fragments derived from rocky shores, or *Tellina* shells derived from estuarine deposits).

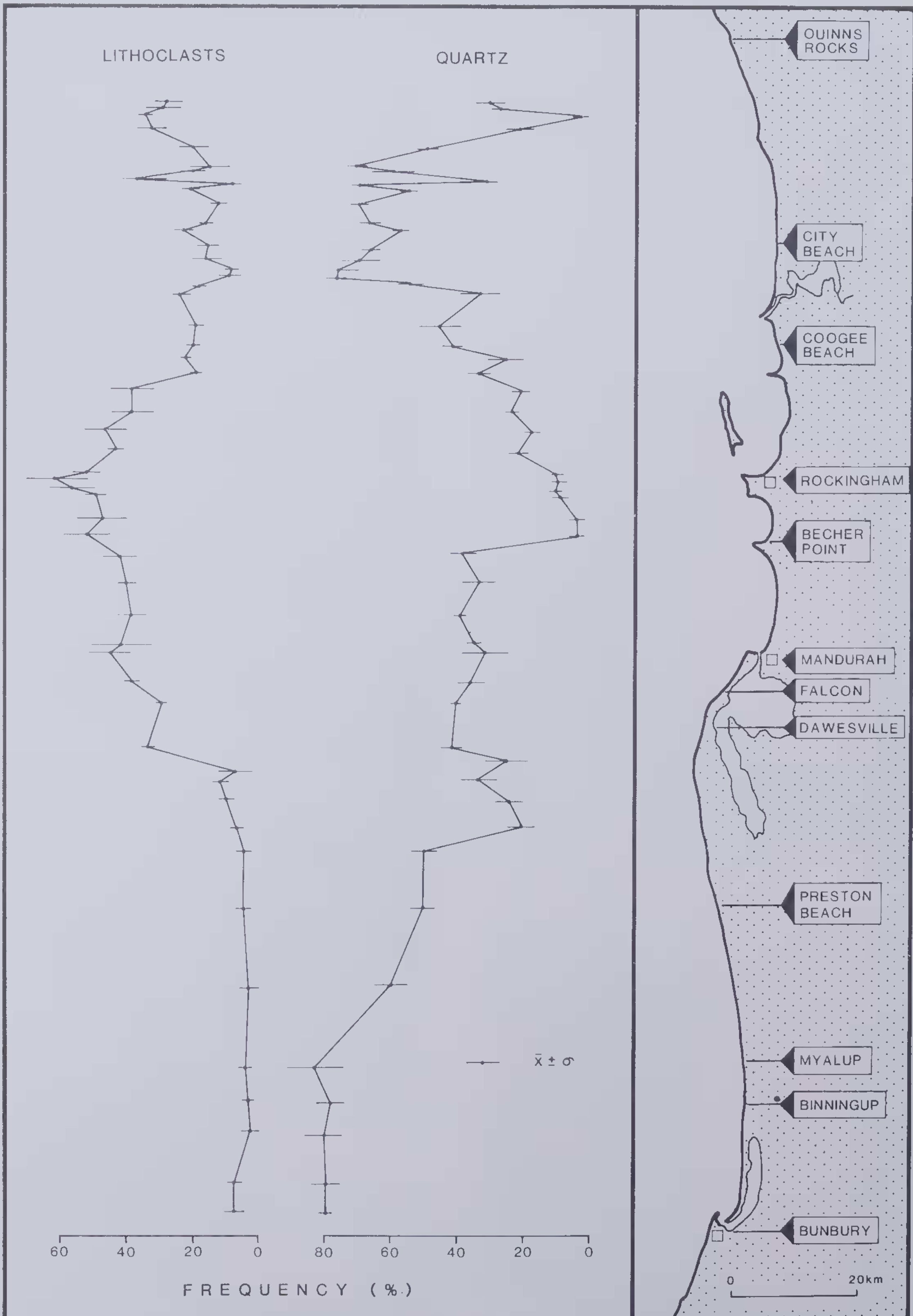

Figure 3 Variation of lithoclasts and quartz in beach sands along the coast between Bunbury and Eglington Rocks. Note the small standard deviation with respect to the mean abundance for the samples.

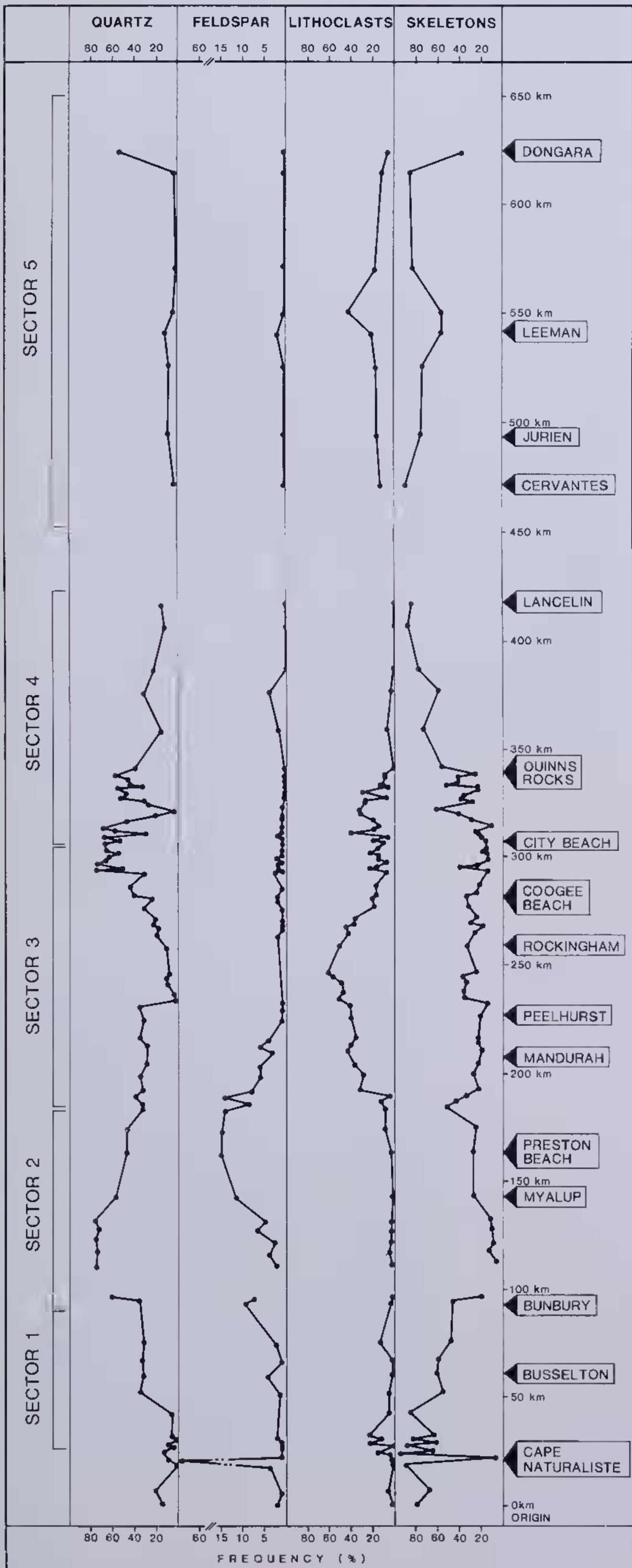

Figure 4 Compilation of results for all sampling sites, in all sectors, for abundance of quartz, lithoclasts, skeletons and felspar.

Regional & local distribution patterns of grain types in beach sand along the Rottnest Shelf coast

The distribution of sand grain types along the beaches of the Rottnest Shelf coast is presented in Figures 2-4. These results show distinctive patterns in each of the 5 sectors from Geographe Bay to Dongara. The results of a local provenance study, to illustrate the typical petrologic patterns of beaches in the Whitfords-Lancelin Sector, are presented in Fig. 2. The various distribution patterns of grain types in the beaches of the various sectors are interpreted below in terms of sediment provenance, supply and transport.

Geographe Bay Sector

Distribution of Grain Types. Data from the pocket beaches of the rocky shores of Cape Naturaliste and from the continuous sandy shore of Geographe Bay itself are discussed here. The pocket beaches of Cape Naturaliste show marked compositional variations between sample locations in adjacent pocket beaches 1 or 2km apart. The quartz component varies from 1 to 22%, felspar from 1 to 78%, lithoclasts from 2 to 26% and skeletons from 6 to 95%. In contrast, the Geographe Bay beaches exhibit a gradual change in composition at the regional scale. In the western portion of Geographe Bay, adjacent to Cape Naturaliste the sand contains high concentrations of skeletons (60-86%) and only minor concentrations of other grains. Progressing along Geographe Bay towards the east and north east, the skeletal component of the sands decreases to 40 or 50% and the quartz component increases to around 30 or 40%. Felspars and carbonate lithoclasts are present in minor concentrations that vary locally but do not exhibit a consistent trend; felspars vary from 1 to 4% and carbonate lithoclasts from 2 to 14%.

Interpretation of Distribution Patterns. The sharp contrast in sediment composition between the pocket beaches of the Cape Naturaliste shore indicates that there is little exchange between these beaches and the open shoreline of Geographe Bay. Local variation in sediment sources and supply cause the differences in sediment composition of the pocket beaches. For example, the occurrence of felspar- dominated lithologies at Bunker Bay contributes to the local concentration of that component in the adjacent beaches.

In contrast, the gradual change in sand composition along the shores of Geographe Bay indicates regional transport and mixing of sediments. The skeletal component is largely derived from the organisms inhabiting the extensive seagrass meadows that cover much of the floor of the bay (Searle 1978), and the supply of skeletons from the meadow to the shore occurs around the entire embayment. Consequently, the decline in skeleton content of sands from west to east is attributable either to selective transport of skeletons, or dilution by quartz sand supplied by the Vasse River system.

Leschenault-Preston Sector

Distribution of Grain Types. There is a significant hiatus in regional beach composition trends at Casuarina Point which separates the pattern of Geographe Bay from that of Leschenault-Preston. At Casuarina Point the beaches are bounded by headlands of basalt, and sands contain 76% skeletons, much higher than Geographe Bay to the south, or the shores of the Leschenault-Preston Sector to the north. In the Leschenault-Preston Sector, quartz dominates the beach sands. Although variable, the quartz content generally declines from 50 or 80% in the south to about 25% in the northern parts of the sector where there are local limestone rocky shores. Skeletons exhibit the reverse trend, generally increasing from less than 11% in the south to 38% in the northern portion of the sector. Lithoclasts form less than 10% of the beach sediment, except in northern localities with limestone rocky shores, where they reach up to 38%. Felspar concentration is variable but minor, locally reaching up to 16% at Preston.

Interpretation of Distribution Patterns. The compositional hiatus at Casuarina Point indicates that transport of sediment between the Geographe Bay and Leschenault-Preston sectors is limited. The coastal barrier in this sector is composed predominantly of quartz sand (80%) which is being liberated by erosion into the littoral transport system (Semeniuk & Meagher 1981, Semeniuk & Searle 1987), and prevailing conditions impell it northwards (Searle & Semeniuk 1985). As a result, quartz dominates the shoreline sands in the southern and middle parts of this sector. The compositional gradient towards the north of decreasing quartz and increasing skeletons is attributable to dilution of quartz by local sources of skeletons and lithoclasts. In the northern part of the sector, rocky substrates supply local sources of lithoclasts and support benthic organisms, which supply skeletal grains into the littoral transport system.

The variable felspar content of sand along this sector may be attributable to local anomalous deposits of felspar-rich sediments (possibly an old drainage channel) near Preston. Under prevailing conditions and storms the felspar is dispersed north and south. The more gradual decline in felspar to the north of Preston reflects the dominance of the prevailing northerly transport.

Cape Bouvard-Trigg Island Sector

Distribution of Grain Types. Between Cape Bouvard and Trigg Island the coast consists of sandy beaches interrupted by limestone rocky shores and this is reflected in the content of lithoclasts. South of Cape Bouvard in the Leschenault-Preston Sector, lithoclasts comprise less than 5% of the beach sediments. North of Cape Bouvard, the lithoclast content varies abruptly and locally between 0 and 45%. North of Mandurah, lithoclasts in the beach sands decline slightly to about 36% until rising again near Becher Point and Rockingham to 50 to 60%. North of Rockingham the lithoclast content progressively declines to less than 25% between Fremantle and Trigg Island. Skeletal grains reflect a similar trend to the lithoclasts.

The quartz content of beaches north of Cape Bouvard remains relatively constant at about 60% before declining abruptly to 30 to 40% near Falcon. At Becher Point the quartz content abruptly declines further from 30 to 40% to about 4%. The quartz content then steadily increases to between 64 to 76% at the northern extremity of the sector in the vicinity of Trigg Island. Felspar concentrations decline from 6% at Cape Bouvard to less than 2% for most of the remainder of the sector.

Interpretation of Distribution Patterns. The distribution patterns of grain types of the beaches in this sector clearly illustrate the local influence of productive seagrass meadow assemblages and extensive linear onshore and offshore limestone ridges (Searle 1984, Searle & Semeniuk 1985). Quartz-dominated sediment that is transported past Cape Bouvard from the Leschenault-Preston Sector is progressively diluted by carbonate sediment generated by the biota of rocky shores and benthic sand/ seagrass assemblages, or by the eroding limestones. Quartz contributes significantly to beaches, however, only as far north as Becher Point.

Beaches on the promontories closest to the eroding offshore ridges (Becher Point and Rockingham) contain the highest concentrations of carbonate lithoclasts. Elsewhere, benthic assemblages are the dominant sediment source. North of Fremantle, the supply of lithoclasts is limited to areas where there is exposure of lithified onshore aeolianite, and where the local seagrass meadow assemblages are less dense and, ultimately, absent. Consequently beach sediments are quartz-rich and tend to reflect the quartz-dominated dune sands that form the adjacent coast.

Whitfords-Lancelin Sector

Distribution of Grain Types. The Whitfords-Lancelin Sector consists of isolated sandy cuspate promontories widely separated by rocky coasts with pocket beaches. Two distinct distribution patterns are evident. Firstly, the pocket beaches vary greatly and abruptly in their content of quartz and lithoclast, with either being dominant; the skeleton content of the pocket beaches is minor but variable. Secondly, in contrast, the beaches of the sandy cuspate promontories are relatively homogeneous with skeletal grains forming a dominant component of the sands.

Interpretation of Distribution Patterns. The marked variation in sediment components between pocket beaches indicates the comparative lack of sediment exchange between adjacent pocket beaches. Consequently these beaches reflect local variation in sediment supply. Along these coasts, quartz is derived from the coastal limestones and from the quartzose sands overlying the limestones. The minor skeletal component is derived from the organisms inhabiting the intertidal to nearshore rocky environments.

The relative homogeneity of the composition of beach sands along the large scale accretionary cusps indicates the ready and efficient transport north and south along the uninterrupted cusp shores. The higher skeleton content of the sands reflects the presence of seagrass meadows that tend to inhabit the sheltered sandy substrates of the adjacent nearshore in the cusp loci. Abrupt compositional differences at the small scale between the cusps and adjacent pocket beach shores indicate little exchange of sediment between the large scale cusps and adjacent limestone rocky shores.

Wedge Island-Dongara Sector

Distribution of Grain Types. The limited number of samples collected in the northern half of the Wedge Island-Dongara Sector shows a general consistent pattern of sand composition, except near river mouths. The mollusc component is relatively high (>40%), the abundance of calcareous algae and lithoclasts are moderately but consistently elevated, *c* 25% and 20%, respectively, and the quartz content is generally low (< 10%). Felspar and heavy minerals generally are absent. At river mouths there may be a substantial input of quartz (*eg* 54% at Dongara) which significantly dilutes the other components.

Interpretation of Distribution Patterns. The overall uniform composition and apparent lack of compartmentalization of composition patterns at the regional scale within this sector suggest extensive alongshore transport and mixing of sediment types. This probably reflects the increased effect of sea-breeze generated windwaves as well as the progressive breakdown in shelter of offshore barriers (Searle & Semeniuk 1985). As a result, the sediment of pocket beaches along rocky shores and those of lengthy beaches of the large scale accretionary cusps are compositionally similar. Lithoclasts and molluscs derived from rocky shore environments are transported alongshore and freely mixed with calcareous algae and molluscs derived from seagrass meadow environments. The only major interruption to this pattern appears to be provided by rivers. Here, aeolian quartz sands of the hinterland are reworked, transported and discharged into the shore environment by rivers of the Murchison region.

Discussion and conclusions

Summary of distribution patterns

The distribution of sand grain types along beaches of the Rottnest Shelf coast shows several general patterns. Firstly, each of the 5 regional sectors between Geographe Bay and Dongara show distinctive patterns of grain type distribution. reflecting variation in source types, biotic assemblages and coastal processes. Quartz grains dominate the Geographe Bay Sector and Leschenault-Preston Sector for lengthy stretches of the coastline, but overall, there is a general decline regionally in quartz sand to the north. Within the Whitfords- Lancelin Sector quartz occurs in high concentration pockets only locally. Skeletal grains are locally abundant where there are nearby sites of extensive seagrass meadows or rocky shores. and lithoclasts also are abundant near sites of eroding limestone. As a consequence, the distribution of skeletal grains and lithoclasts may be markedly restricted geographically, and there may be a tendency for compartmentalization of sediment types containing these grains along the coast. Regionally there is a decline in abundance of heavy minerals to the north and felspar also is noted to occur mainly in the Geographe Bay and Leschenault-Preston Sectors.

Compositional trends of sands are uniform along the Geographe Bay and Leschanault Preston Sector. However, compositional trends are compartmentalized at the scale of the accretionary cells in the Cape Bouvard-Trigg Island Sector, and are markedly compartmentalized at the scale of pocket beaches and individual accretionary cusps in the Whitfords-Lancelin Sector. Pocket beaches along rocky shores, such as the northern part of the Leschenault-Preston Sector and throughout the Whitfords-lancelin Sector, also contain local high-concentration patches of lithoclasts. The skeletal grains on beaches of accretionary cusps in the Cape Bouvard-Trigg Island Sector and Whitfords-Lancelin Sector have sources in seagrass meadows in the nearby marine environment, and accordingly there is a concentration of molluscs and calcareous algae in these areas.

Significance of results

The results of this paper highlight several aspects of littoral transport that are important in understanding coastal processes. and that are useful in coastal management. Firstly, the results serve to identify the major pathways of sediment transport in the littoral zone of southwestern Australia. This has implications for coastal management in that it is possible to link coastal stability, or structures that result in coastal realignment, or activities that result in depletion of sediment supply, to some prominent and extensive pathways as identified by provenance studies. Secondly, as a corollary to the above, the results also indicate that transport in the littoral zone may involve lengthy and extensive pathways (or littoral streams) in some regions (*eg* the Leschenault-Preston Sector), but may be only small scale and compartmentalized in other regions (*eg* the Whitfords-Lancelin Sector). This aspect also has implications for coastal management in that the design of coastal structures and the management of coastal processes must be designed specifically to the various coastal sectors or sub-sectors in the region. Sediment transport rates and transport styles from one locality accordingly should not be indiscriminately applied to other areas, and should not be viewed as necessarily indicative of regional patterns.

Thirdly, the results indicate that there are various sources of sediment available for beaches, and that these can vary in their storage volumes and supply rates. However, it is also possible that the variation in composition and the gradual changes in abundance of specific grain types in beaches can indicate or reflect the varying coastal processes involved in supplying, transporting and emplacing the various grain types. This aspect of beach sand petrology, when used in conjunction with other coastal process information, can provide valuable insight into the long term aspects of coastal history, transport, or coastal stability. Finally, sediment provenance, when used in conjunction with other studies such as stratigraphy. oceanography, accretion/erosion rates and geomorphology, can provide an indication of volumes of sediment being transported along the littoral zone.

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